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Scale-Modeling of Inert Pressurant Distribution as Applied to Fire Extinguishment By Nitrogen Pressurization

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An approximate method for scale-modeling inert pressurant distribution in geometrically similar enclosures is applied with length scale factors of 3.84, 6, and 23 (prototype to model) for turbulent flow conditions. Modeling correlations are best in spaces with minimal clutter (no obstructions to flow). With considerable clutter, however, correlations were considered acceptable and indicated good mixing within less than an additional injection time.

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SCALE-MODELING OF INERT PRESSURANT DISTRIBUTION AS APPLIED TO FIRE EXTINGUISHMENT BY NITROGEN PRESSURIZATION

INTRODUCTION

As a method of controlling unwanted fires in enclosed pressurizable spaces, Carhart and Fielding [1] proposed pressurization with nitrogen gas. The inert gas added to such an enclosure suppresses fire yet maintains a life-supporting atmosphere [2]. Other advantages include the inertness of the gas to mechanical and electrical systems, its cleanliness, and the relative ease of restoring a space to normal use after a fire. If the oxygen concentration of a space is reduced to the range of 12 to 14% by volume, hydrocarbon flames will be extinguished [3]. Thus, space pressures must be increased from 1 to about 1.8 atm to meet this requirement. Findings of laboratory studies have supported this fire-suppression concept [4-6]. However, in rapid injections of pressurant gas into large systems questions arose which needed answers if a practical system were to be developed. Would pockets of oxygen-rich gas form which could exacerbate fire, or would oxygen-poor regions be generated which could endanger survivability? How would clutter (such as machinery, cabinets and furnishings) in the space affect gas mixing? Could gas-mixing rates in laboratory tests be used to predict those in real systems?

To address questions such as these, we chose an experimental or scale-modeling approach rather than a theoretical one. The latter would require numerical flow-field calculations in the presence of turbulent transport. In addition, most practical spaces because of their geometric complexities would required a three-dimensinal treatment. At present, the success of such a calculation is questionable. On the other hand, geometric complexity is handled conveniently by model fabrication. Further, the number of independent nongeometric dimensionless flow parameters in this case is small and favorable to experimental modeling.

Mixing of injected pressurant into resident gases in enclousures is dominated by turbulence driven by the rapid injection of the pressurant gas. Since the effects of fire-induced, free-convection plumes are small in comparison, no actual fires were used in these studies. A scale-modeling hypothesis was formulated based on a rigorous similarity analysis and practical considerations [7]. It predicts first-order characterization on pressurant mole-fraction histories for homologous points in geometrically similar enclosures and gives an upper bound on the local pressurant concentration time lead or lag relative to the enclosure mean concentration. One evaluation is made in a single chamber showing the effect of a flow obstacle on pressurant distribution. Then comparisons are made at homologous points in space and time in geometrically similar enclosures of different sizes with and without a flow obstacle.

EXPERIMENTAL

Gas-mixing experiments were performed in three chambers. The 324-m^3 chamber (named FIRE I) [8] and the 5-m^3 chamber [9-13] are at the Naval Research Laboratory (NRL), and the 1/6th scale model [14] of the NRL 5-m^3 chamber is at the University of Washington (UW). Each chamber is geometrically similar with a length-to-diameter ratio of 1.8. Length scale factors of FIRE I to the NRL 5-m^3 and the UW model chambers are 3.84 and 23, respectively.

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FIRE I is a horizontal cylinder with hemispherical ends; its diameter is 5.85 m (19.2 ft). Figure 1 shows a sketch of elevation, plan, and end views with three nozzle locations and two thermocouple array positions. Figure 2 gives each of the 13 thermocouple locations for array position 2 along the chamber centerline and shows a flow-obstacle location. The obstacle was 2.67 m high and extended 0.74 m above the chamber centerline. The top, bottom, and three sides were closed; the fourth was covered with screen wire (15 openings per 25.4 mm (1 in.) with a wire diameter of 0.3 mm (0.010 in.)) [15].

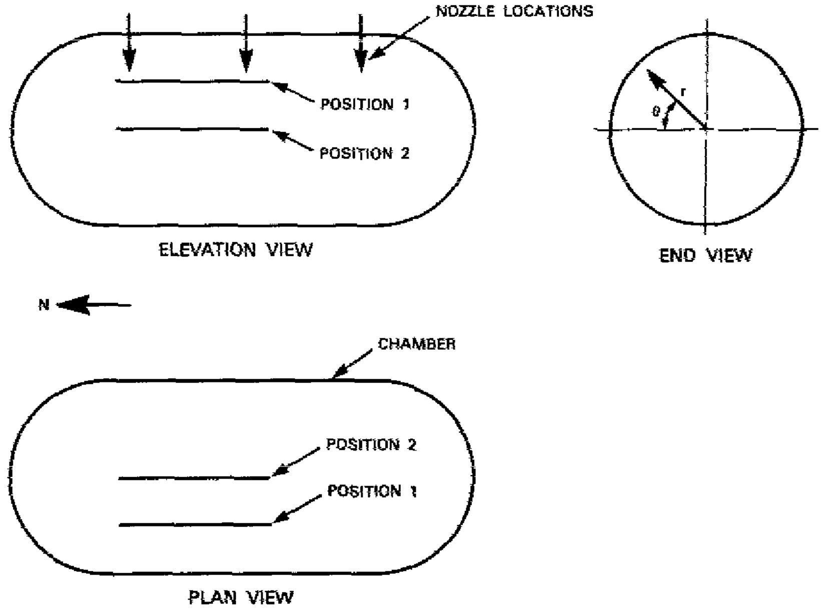

Fig. 1 – Elevation, plan, and end views of FIRE I, showing three nozzle locations and two thermocouple array positions. Chamber diameter is 5.85 m (19.2 ft).

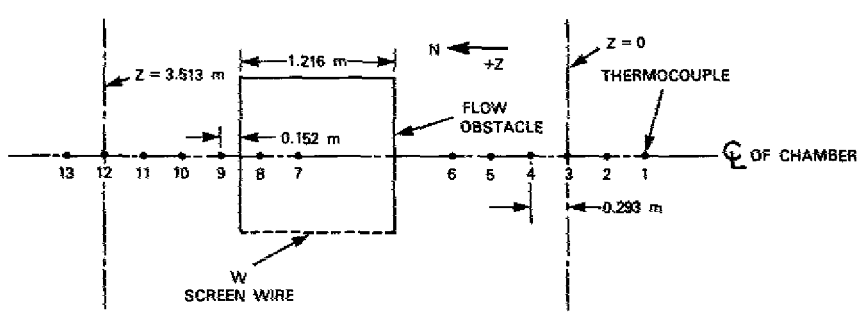

Fig. 2 – Plan-view schematic of FIRE I interior giving obstacle and thermocouple locations along the centerline relative to the vertical plane $z = 0$

Experimental procedure, briefly, was as follows. Pressurized nitrogen gas was injected through nozzles into the chamber, thus increasing pressures from 1 atm ambient air to approximately 2 atm. In the NRL experiments, the pressurant gas concentrations in the mixture were determined by a thermal method in which the temperature differences of the pressurant and resident gases were exploited. Local temperature histories were measured with fine-wire thermocouples, and local pressurant mole-fraction histories were inferred from a thermodynamic analysis [16]. In the UW experiments, pressurant gas was doped with CO_2 and local pressurant concentration histories were directly determined by a continuous probe sampling and analysis of a small gas stream [14]. Injection times of pressurant gas varied from approximately 10 to 30 s, depending on the number and diameter of nozzles.

RESULTS AND DISCUSSION

FIRE I

Local mean pressurant mole-fractions X are plotted versus dimensionless time τ in Fig. 3 with the flow obstacle in place and the screen side facing north. Pressurant was injected from only the south nozzle, the most severe configuration for mixing. Five local I-locations are shown, 6, 2, 8, 9 and 7; 7 and 8 are inside the obstacle. The solid line shows a condition of perfect mixing. We calculate this condition at any time t by assuming instantaneous and perfect mixing of the moles of pressurant added N with the moles of air initially present N_0 in the chamber, thus giving the chamber average pressurant concentration at time t

$$\bar{X} = N/(N + N_0).$$

During pressurant injection, we define τ as

$$\tau = X/\bar{X} \qquad t \leqslant t_c$$

where time $t = t_c$ when the pressurant control valve is closed and $0 \leqslant \tau \leqslant 1.0$. For postpressurant injection $\tau > 1.0$, it is defined as

$$\tau = 1 + (t - t_c)/\theta_c \qquad (t > t_c)$$

where $\theta_c = -[dln(1 - X)/dt]^{-1}$ and is determined just prior to time $t = t_c$.

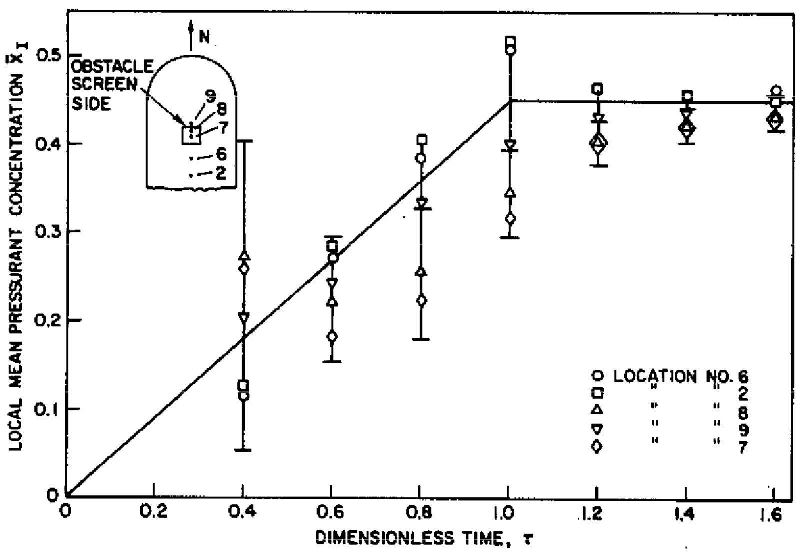

Fig. 3 – FIRE I local mean pressurant concentration (mole-fraction) vs dimensionless time for five centerline locations with the south nozzle and flow obstacle, screen side facing north. Error bar is ± one standard deviation for location 8.

Those measured local concentrations that fall below this line of perfect mixing show a pressurant deficiency, and those that fall above it a pressurant excess. Figure 3 shows deficiencies for three positions behind the flow obstacle. However, when $\tau = 1.6$, the data show that good mixing is attained. Error bars for I-location 8 show ± 1 standard deviation. Figure 4 gives data for the same test configuration, except there is no flow obstacle. Again, the data show a pressurant deficiency but a less severe one. In this case, good mixing is signaled by a τ-value of 1.2.

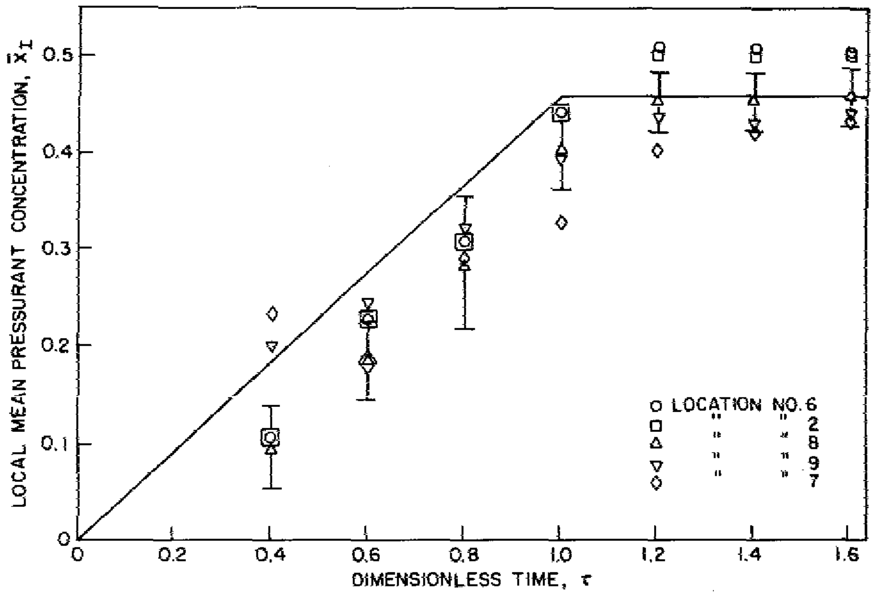

Fig. 4 – FIRE I local mean pressurant concentration (mole-fraction) vs dimensionless time for the same fire centerline locations as Fig. 3 with three nozzles and no flow obstacle. Error bar is ± one standard deviation for location 8.

MODEL-PROTOTYPE COMPARISON

Our scale-modeling hypothesis states that, for a given enclosure geometry and nozzle configuration, at homologous model and prototype points, dimensionless pressurant deviation ξ is a unique function of dimensionless time τ, regardless of pressure level or rate. We describe ξ as

$$\xi = (X - \bar{X})/\bar{X}_c$$

where X is the pressurant mole-fraction at any time t, $\bar{X}$ is the perfectly mixed chamber average pressurant mole-fraction at time t, and $\bar{X}_c$ is the value of $\bar{X}$ at time $t = t_c$ (t_c is the time of pressurant control valve cutoff).

Figure 5 gives model and prototype data with flow obstacle (see Fig. 2). Data are from both NRL chambers and the UW model at $z/L = 0.57$ along the centerline. This corresponds to I-location 10 in Fig. 2. During pressurant injection ($0 \leqslant \tau \leqslant 1$), the UW model experiment shows greater pressurant deficiencies (ξ-values are more negative) than the FIRE I and 5-m^3 experiments. This difference may result from our method of determining moles of pressurant-added N in the latter two experiments. In this method, at any time t, chamber content average temperature is taken as the arithmetical average of the 13 measurements and applied, with average pressure, to the Gas Law in determining N. The presence of the obstacle may affect this average. Nonetheless, at values of $\tau > 1.0$, Fig. 5 shows improvement in the correlation and reasonable evidence that good mixing is quickly achieved at τ-values of 1.5 to 1.6.

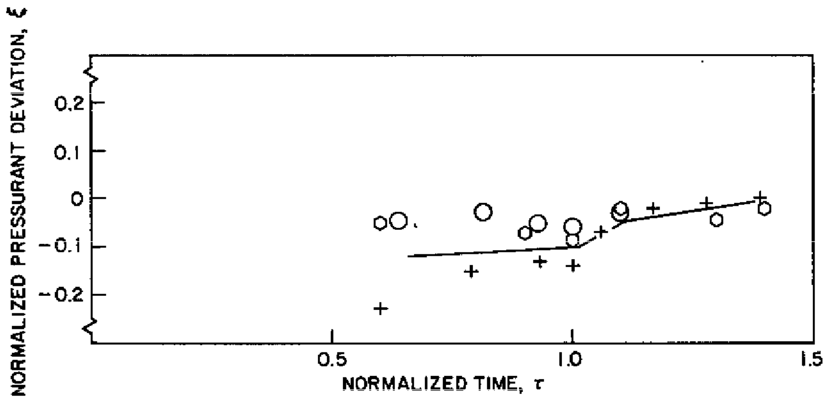

Fig. 5 – Model-prototype comparison with obstacle. Data are for location 10 in Fig. 2 (O) and homologous locations for UW model (+) and NRL 5-m^3 (○).

Figure 6 makes the same comparison of model and prototype as Fig. 5, except with no flow obstacle. Figure 6(a) shows data at $z/L = 0$. This location is in the center nozzle jet (three nozzles are used). The NRL experiments show a pressurant excess during pressurant injection ($0 \leqslant \tau \leqslant 1$) that exceeds the model prediction. Again, however, during postinjection ($\tau > 1$), good mixing is achieved ($\xi \approx 0$) by $\tau = 1.2$. In Fig. 6(b), at $z/L = 0.44$, normalized pressurant deviations ξ correlate both during and after pressurant injection, and good mixing is achieved by $\tau = 1.2$. At low values of τ (0.6 to 0.8), values of ξ for FIRE I are somewhat lower than predicted either by the UW model or by the NRL 5-m^3 experiments.

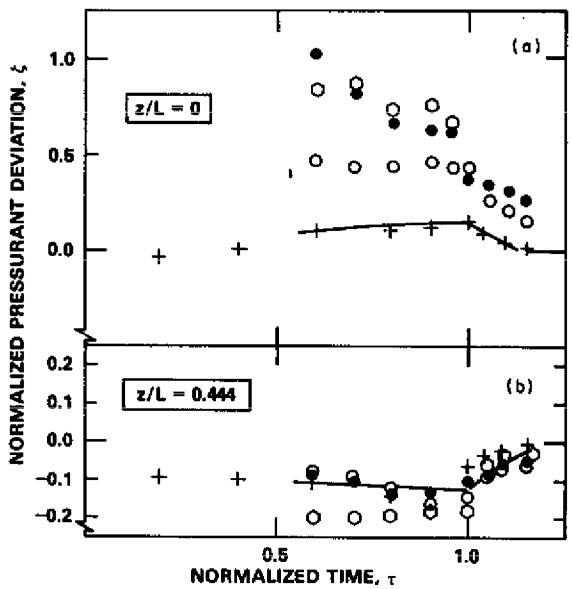

Fig. 6 – Model prototype comparison without flow obstacle. Example comparisons of centerline data for NRL FIRE I (O) and 5-m^3 experiment with 25.4-mm (•) and 15.2-mm (○) nozzles and for UW model experiment with initial pressures of 1 and 6 atm (+).

CONCLUSION

We have demonstrated an approximate method for the scale modeling of inert pressurant distribution in geometrically similar, pressurizable enclosures. Three chamber sizes have been used. The largest, FIRE I, 324 m^3 in volume and 5.85 m in diameter, approaches full size of a submarine compartment. Length scaling factors of it to the NRL 5 m^3 and the UW model chambers are 3.84 and 23, respectively.

We obtain best modeling correlations with no flow obstacles in the spaces and away from incoming jets. Pressurant gas concentrations in incoming jets measured in the NRL experiments are high as compared to values estimated according to Ricou and Spalding [17] and as determined in the UW experiment. We explain this difference as inaccuracies in certain assumptions necessary in the NRL thermal method of measuring pressurant concentrations using local temperatures.

With addition of flow obstacles into spaces, accuracy of the modeling correlation decreases. However, our limited work with obstacles indicates that reasonable estimates of mixing times can be expected except for severe clutter (such as in a locker or cabinent with leakage only around doors).

Our studies indicate that three conditions are necessary for successful modeling of fire extinguishment by nitrogen pressurization: (1) that estimated mixing times to within a few seconds be acceptable, (2) that pressurant injection be rapid (10 to 12 s preferable and always less than 30 s), and (3) that injection nozzle flow be Mach 1. Such rapid injection can be expected in practice. Otherwise, a well-developed fire in an occupied closed space could render it unihabitable during extinguishment.

Additional experiments with a graduated flow-obstacle severity would better define limits of this scale-model approximation. Further, a better measure of pressurant flow rate and an increased number of local measurement points would improve accuracy of the larger-sized NRL experiments. However, in a practical sense, the need for increased accuracy must be weighed against a given set of requirements.

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